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Published in:
Procedia CIRP

Link to article, DOI:
10.1016/j.procir.2017.11.021

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 69 (2018) 451 – 456

www.elsevier.com/locate/procedia

25th CIRP Life Cycle Engineering (LCE) Conference, 30 April – 2 May 2018, Copenhagen, Denmark

Prospective assessment of steel manufacturing relative to Planetary Boundaries: Calling for life cycle solution

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Abstract

Steel, as one of the largest consumed materials is a large contributor to climate change accounting for about 7% of annual human induced CO_2 emissions. Using material in-use stock modelling and dynamic life-cycle assessment, this study predicted the share of the safe operating space for climate change that will be occupied by steel production between 2015 and 2100. Results show that if current practice is continued, steel manufacturing will occupy what corresponds to about 50% of the safe operating space for climate change by 2100, indicating an urgent need for impact reducing strategies to stay within the safe operating space.

Peer-review under responsibility of the scientific committee of the 25th CIRP Life Cycle Engineering (LCE) Conference

Keywords: Planetary Boundaries; Absolute sustainability; Steel manufacturing; Life cycle assessment

1. Introduction

The increasing size and resource consumption of the human enterprise has begun to affect and destabilize key Earth System processes [1]. To protect the stability of the Earth System, Planetary Boundaries were proposed to define a safe operating space for humanity to develop and thrive [1]. In particular, material consumption which serves as the basis for prosperity is problematic due to the massive production, consumption and the associated environmental footprint [2]. Nevertheless, material consumption is still expected to rapidly increase to meet the demands of an increasing and more affluent future population [3]. Indeed, to accommodate a larger global population while also avoiding putting additional pressure on the Earth, there is a need for exploring the impact and contribution of key anthropogenic activities with regard to Planetary Boundaries, especially in the production and consumption of fundamental materials.

Iron and steel (steel, afterwards) is one of the most fundamental materials to underpin humanity's prosperity and in 2009 accounted for about 7% of global annual human induced CO_2 emissions in its processing [4–6]. Last century has witnessed a factor 20 growth in extraction and processing of iron ore [7] driven by population and affluence growth. Given our current reliance on steel, this trend is expected to continue in the future [8], and previous studies have identified that steel should be produced in an increasing scale to meet future needs [9]. However, research into the environmental impacts associated with such growth is limited. Measures for reducing greenhouse gas (GHG) emissions in the steel industry tend to focus on improving energy efficiency, implementation of less carbon intensive or carbon reducing processes, and material efficiency. Quader et al. [10] conducted an in-depth review of recent and future technological advancements for reducing GHG emissions from steel production via improvement of energy efficiency and development of new processes. The most promising

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doi:10.1016/j.procir.2017.11.021

measures include carbon capture and storage, new iron and steel making processes (direct- and smelting reduction processes), hydrogen-based steel making, iron ore electrolysis, and biomass based steel production. Material efficiency aims to reduce the material input needed to meet future needs [11–13]. Options for reducing carbon emissions through different material efficiency strategies have also been identified [9,14–16], e.g. increasing supply of end-of-life scrap which has lower GHG emissions than primary steel production [17,18].

However, there is a lack of understanding of how future change in anthropogenic steel use will affect our performance with regards to Planetary Boundaries. A number of studies have looked into how the implementation of the GHG reducing measures may affect future GHG emissions e.g. [19–24]. These studies confirm that technical solutions can reduce GHG emissions, but their results are not compared to absolute targets to indicate whether the magnitudes of impacts and reductions are substantial. Only few studies have related the impacts to absolute targets [11,25–27], and these studies have focused on annual GHG emissions which is not a good indicator for climate change because the principal driver of long-term climate warming is the total emissions of CO_2 and every tonne of CO_2, no matter when it is emitted, contributes almost equally to global warming [28].

To establish a baseline for steel production on which to base future environmental policy, this study sought to quantify climate impacts of steel production between 2015 and 2100 when keeping steel production technology constant over time. The research question posed in this study was: *If future steel producing technologies remain at current business-as-usual, how will greenhouse gas emissions from steel production develop in a world where population and affluence is increasing, and how will the associated climate change impacts relate to the Planetary Boundaries?* The results of this study provide an indication of the impacts potentially occurring if a business-as-usual approach is retained. Indeed, this gives a worst-case estimation of the magnitude of the problem and indicates the level of reductions required in the steel producing and consumption relative to current practice.

2. Methodology

This study reconciles the two well established life cycle engineering approaches, material flow analysis (MFA) and life cycle assessment (LCA), to predict the future steel flows and their associated environmental impacts. MFA (Section 2.1) helps to quantify flows and stocks of global steel from cradle to cradle perspective, which can take into account the changes in population and affluence through its stock-based dynamics. Meanwhile, LCA (Section 2.2) is adopted to analyze the environmental impacts of each steel processing technology. By combing these two approaches, this study can obtain the overall impacts caused by the future anthropogenic steel use. Furthermore, this study applies a novel approach to link the total impacts of steel production to the requirements presented by the Planetary Boundaries (Section 2.3).

2.1. Predicting steel production between 2015 and 2100

The annual flows and stocks in the steel cycle from 2015 to 2100 are estimated, covering all stages in the entire life cycle (i.e. Mining, Primary production, Products fabrication, In-use, Recycling and Secondary production). This MFA focuses on tracking one element "Fe" in iron and steel products along its full cycle, other related elements, such as alloying elements, are included as inputs for steel making in the LCA, but are, otherwise, not included in the MFA. A typical dynamic material flow model is applied for each life stage with specific treatments in the use stage. The products fabrication and recycling stages for steel are divided according to the end-use sector into: Construction, Machinery, Transportation, and Other Products. The parameters for these three life cycle stages are specified according to the end-use sector's product features. The key parameters for end-use products (i.e. market share, lifetime, recycling rate, etc.) are adopted from [29].

The steel stocks and flows from 2015 to 2100 are obtained annually based on the stock-driven approach. The estimation involves three elements: population trend estimation, per capita steel in-use stock growth, and changes in mass efficiency of each life stage. The mass efficiency of each life stages change is assumed to stay at the level of current technology.

The basic settings for the other two elements are as follows. The estimation of the future population comes from the "World Population Prospects" published by United Nations Population Division [30] where the medium scenario for population projection till 2100 are used, with an estimated global population around 9.7 billion in 2050 and 11.6 billion in 2100. Increased future material affluence is expressed as the in-use stock which is well studied in industrial ecology [26,31]. The future growth of stock is assumed to follow the saturation hypothesis as proposed by Müller and Wang [32], observing that most developed countries follow a similar saturation pattern of steel use. This saturation trend was described by a Logistics function from Pauliuk et al. [16] which predict the future trend of in-use stock per capita. The per capita in-use stock is predicted to increase from about 4.4 tonnes per capita in 2015 to 8.5 tonnes per capita in 2050 and 11.8 tonnes per capita in 2100.

2.2. Modelling steel production and associated environmental flows

A bottom up modelling approach was chosen for future steel production because it facilitates differentiation of the steel making process into individual processes, which makes it easier to assess the contribution of different life-cycle processes, e.g. primary versus secondary production. A general overview of the model is shown in Figure 1. The processes and their GHG emission factors used for modelling steel production are given in Table 1.

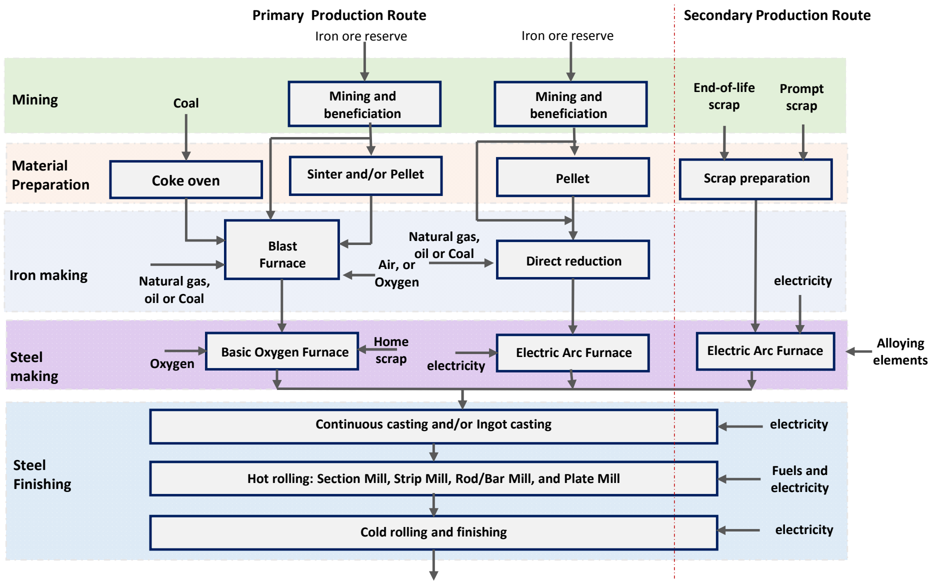

Fig. 1. Schematic overview of the bottom-up steel production model used for estimating GHG emissions from cradle-to-gate steel production

Table 1. Processes used for modelling current and future steel production including emission factors for carbon dioxide, methane and nitrous oxide for each process. The emission factors include direct process emissions and indirect emissions from energy and material inputs necessary for running the process, except emissions related to processes also shown in the table.

	Kg emitted per kg process output			
Processes	CO_2	CH_4	N_2O	Reference
Mining	2.6×10^{-1}	6.0×10^{-4}	2.7×10^{-5}	[33]
Sintering	3.2×10^{-1}	6.7×10^{-4}	4.8×10^{-6}	[33]
Pelletizing	7.6×10^{-2}	4.6×10^{-4}	3.5×10^{-6}	[33]
Direct reduced iron	1.0	4.6×10^{-3}	2.0×10^{-6}	[33,34]
Blast furnace	1.1	6.5×10^{-3}	1.2×10^{-5}	[33]
Basic oxygen furnace	6.1×10^{-1}	4.1×10^{-4}	3.4×10^{-5}	[33]
Electric arc furnace	3.0×10^{-1}	-1.7×10^{-4}	3.1×10^{-5}	[33]
Continuous casting	1.1×10^{-2}	4.6×10^{-5}	1.4×10^{-6}	[35]
Ingot casting	4.6×10^{-2}	1.3×10^{-3}	1.4×10^{-6}	[35]
Section mill	2.6×10^{-1}	8.9×10^{-4}	1.1×10^{-5}	[33,36]
Rod/bar mill	1.9×10^{-1}	6.5×10^{-4}	8.9×10^{-6}	[33,36]
Plate mill	2.7×10^{-1}	9.5×10^{-4}	1.0×10^{-5}	[33,36]
Strip mill	1.9×10^{-1}	6.6×10^{-4}	9.7×10^{-6}	[33,36]
Cold rolling	2.3×10^{-1}	7.3×10^{-4}	1.8×10^{-5}	[33]

The share between sintering and pelletizing of the mined iron ore was assumed to be 30% sintering and 60% pelletizing. The justification for this assumption is that according to World Steel yearbook, sintering of iron ore decreased from 100% in 1950 to 30% in 1990 and from then on stayed at 30% due to implementation of pelletizing as a more advanced preparation technology [37]. The share between blast furnace and direct iron reduction (DRI) was found to be 93% and 7% respectively [5]. The share between basic oxygen furnace (BOF) and electric arc furnace (EAF) for primary steel production was found to be 91% and 9% respectively [5]. The share between BOF and EAF for secondary steel production was found to be 37% and 63% respectively [5]. The division between continuous casting and ingot casting was found to be 97% and 3% respectively [38,39]. The share between mills was based on Cullen et al. [5] as section mill (8%), rod/bar mill (38%), plate mill (11%), and strip mill (43%).

2.3. Estimating contribution of steel production to climate change

The contribution of the steel production to climate change was calculated by estimating the mass of GHGs in the atmosphere as a consequence of emissions during steel production (Eq. 1).

$$m_{GHG}(t) = \sum_{n=1}^{t} E_{GHG}(t_n) \times fr_{GHG}(t) \quad (1)$$

Where $m_{GHG}(t)$ is the mass of a GHG in the atmosphere at year t. $E_{GHG}(t_n)$ is the emission of a GHG at year tn with n going from 2015 to 2100. $fr_{GHG}(t)$ is the fraction of the GHG emitted in year t_n that remains in the atmosphere in year t. $fr_{GHG}(t)$ was estimated based on Shine et al. [40] according to Eq. 2 for all GHGs, except CO_2. The removal of CO_2 is more complex and requires a model that takes the different removal mechanisms into account (Eq. 3).

$$fr_{GHG}(t) = \exp^{\left(\frac{-t}{\alpha_{GHG}}\right)} \quad (2)$$

Where α_{GHG} [yr] is the atmospheric life-time of the GHG, e.g. 12.4 years for methane [41].

$$fr_{CO_2}(t) = a_0 + \sum_{i=1}^{4} a_i \times \exp^{\left(\frac{-t}{\alpha_i}\right)} \quad (3)$$

Where a [-] and α [yr] are specific coefficients and time constants for the removal processes in the decay function for CO_2 in the atmosphere based on the revised version of the Bern Carbon cycle model. Here a_0 = 0.212, a_1 =0.244, a_2 =0.336, a_3=0.207, α_1= 336.4 years, α_2=27.89 years, and α_3=4.055 years [42].

The concentration of a GHG in the atmosphere at time t as a result of emissions from steel production was estimated according to Eq. 4.

$$C_{GHG}(t) = m_{GHG}(t) \times \frac{10^6\ ppmv / m_{air}}{M_{GHG} / M_{air}} \quad (4)$$

Where m_{air} is the mass of the atmosphere (5.15E+18 kg [43]), M_{GHG} is the molar mass of the GHG and M_{air} is the molar mass of air (=28.97 g mol^{-1} [41]). The change in radiative forcing (RF) and change in temperature (T) from GHG emissions was estimated according to Eq. 5 and Eq. 6 respectively.

$$RF_{GHG}(t) = \sum m_{GHG}(t) \times A_{GHG} \quad (5)$$

$$T_{GHG}(t) = RF(t) \times \lambda \quad (6)$$

Where A_{GHG} is the specific radiative forcing of the GHG [Wm^{-2} kg^{-1}] and λ (=1.06 $K(Wm^{-2})^{-1}$ [41]) is a climate sensitivity parameter which indicates the change in equilibrium surface temperature per unit radiative forcing. The sum across all emitted GHGs from the steel system gives the total RF(t) and T(t) associated with global steel production.

3. Results

3.1. Steel production from 2015 to 2100

Figure 2 shows the predicted future crude steel production from 2015 to 2100, differentiated as total steel production, primary production, and secondary production. The results show that although steel production in general will continue to increase throughout the 21st century, primary steel production will peak around 2045 due to increased secondary production. Secondary production will become larger than primary production and dominate the steel making process around 2065. As the end-of-life scrap is the main material source for secondary production, end-of-life scrap will become quite abundant during this period when the large amount of historical steel products enters their end-of-life.

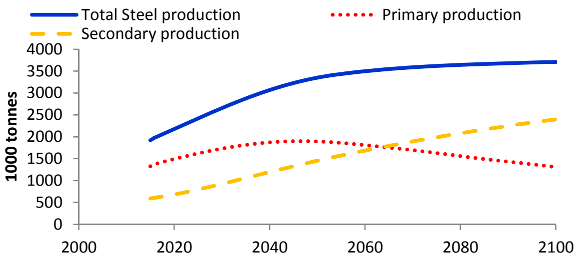

Fig. 2. Development in global steel production between 2015 and 2100 shown for total steel production and for primary and secondary steel production.

The increase of secondary product will gradually meet the final steel products' needs where additional increase in primary production is not required. A complete closing of the steel loop is not observed because (a) the secondary production cannot entirely supply the future needs and (b) some primary steel is still required due to material losses in the steel life cycle and to ensure sufficient steel quality.

3.2. Environmental impacts

For the development in emissions of CO_2, CH_4 and N_2O (Figure 3) from steel production between 2015 and 2100, a peak is observed for all three around 2045, coinciding with the peak observed for primary steel production in Figure 2. The ensuing reduction in GHG emissions is due to overall lower GHG emissions associated with secondary production compared to primary production. However, it should be noted that emissions for all three GHGs will be higher in 2100 compared to 2015 which is due to the higher demand for steel as a result of a larger and more affluent global population.

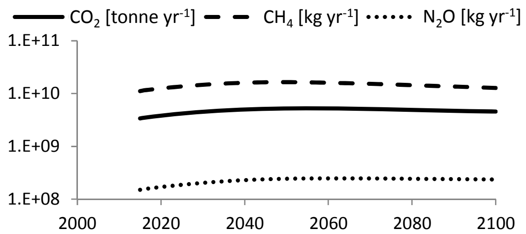

Fig. 3. Development in emissions of CO_2, CH_4 and N_2O from global steel production between 2015 and 2100.

As mentioned above, the most problematic steel production processes, in terms of climate change, are the iron producing technologies i.e., the blast furnace and the direct iron reduction. Indeed, both processes lead to high CO_2 emissions as a result of reducing the iron ore where oxygen in the iron ore reacts with carbon (either as coke or natural gas) to form CO_2.

The GHG emissions modelled in our study are comparable to what has been found in other studies. We estimated a CO_2 emission intensity of 1.76 t CO_2 per tonne steel produced in 2015 which agrees well with an estimated emission intensity of 1.9 for 2015 as reported by World Steel Association [4]. Given uncertainty related to modelling and inherent variability in steel production and associated CO_2 emissions, the modelled intensity also matches with other studies reporting CO_2 emission intensities ranging from 1.3 to 2 tonne CO_2 per tonne steel produced [8,11].

Figure 4 shows the impacts of GHG emissions from steel production in the metrics of the Planetary Boundaries for climate change i.e., radiative forcing [Wm^{-2}] and atmospheric CO_2 concentration [ppm CO_2]. The pattern for both indicators is similar in showing a steady increase from 2015 to 2100 with no indication of peaking in the near future. While CO_2 is the only contributor to atmospheric CO_2 concentration, CO_2 is also the largest contributor to radiative forcing accounting for about 80% of the total impact, followed by methane accounting for about 19% while nitrous oxide account for about 1%.

The Planetary Boundary for climate change was defined by two control variables being 1 Wm^{-2} and 350 ppm CO_2 for radiative forcing and atmospheric CO_2 concentration respectively. Pre-industrial indicator levels were 0 Wm^{-2} and 278 ppm CO_2 respectively [44], hence, the safe operating space is 1 Wm^{-2} and 72 ppm CO_2 respectively. Both Planetary Boundaries are currently exceeded with current control variable values being about 2.3 Wm^{-2} and 396.5 ppm CO_2 [44]. With regards to steel production and the associated emissions from 2015 to 2100, this would by 2100 lead to an increase in the climate control variables of 0.5 Wm^{-2} and 29 ppm CO_2. As shown in Figure 4, this corresponds to about 50% and 40% of the total safe operating space for radiative forcing and atmospheric CO_2 concentration respectively, leaving little space for historical emissions and for other anthropogenic activities.

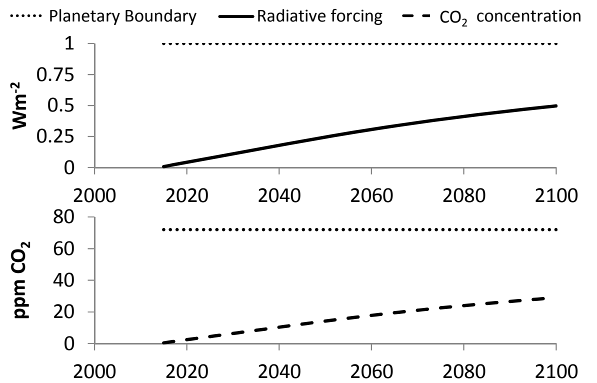

Fig. 4. Change in radiative forcing and CO_2 concentration resulting from steel production from year 2015 to 2100.

4. Discussion

4.1. Need for improving steel production under Planetary Boundaries and life cycle strategies to assist sustainable production and consumption

The results indicate that GHG emissions from steel production will occupy what corresponds to about 50% of the safe operating space by 2100 and results indicate this share to further increase after 2100. This indicates a need for reducing GHG emissions associated with steel production. This need is underlined by the fact that the safe operating space for climate change is already exceeded from historical emissions and because other GHG emitting human activities (e.g. food production and transportation) will also contribute to climate change and occupy a share of the safe operating space.

Three options are proposed in this study to reduce the climate impacts of steel production. The first two relate to the production technology while the last relates to steel consumption. Firstly, implementation of better technologies with lower GHG emissions are necessary, such as implementation of carbon capture and storage (CCS) technology for iron producing technologies which currently result in large CO_2 emissions. Secondly, material efficiency should be increased to ensure that material losses throughout the steel life cycle are minimized. This is especially important for maximizing the use of secondary steel which has a lower impact on climate change compared to primary steel production. Lastly, there is a need for reducing steel consumption, which means that changes in consumption patterns are required, e.g. switching towards a service-based or sharing economy or through dematerialization strategies (e.g. shifting towards more light-weight structures) aimed at reducing the per capita in-use stock. Based on steel production's relatively large contribution to climate change relative to the Planetary Boundaries, a combination of the different measures are likely required and focusing on only one or two will not be sufficient for achieving the required reductions in GHG emissions [45].

4.2. Calls for life cycle engineering solutions towards absolute sustainability

Previous studies have focused on improving production technologies to reduce environmental impact. However, this focus needs to be extended with a cradle-to-cradle view in order to operationalize the alternative strategies mentioned above. Life Cycle Engineering (LCE) plays a crucial role in achieving this. However, traditionally, the technology factor has been the main focus in LCE activities and products have been improved in relative terms based on life cycle performance [46] with tools like LCA, eco-design, design-for-environment, etc. Recognizing the safe operating space for humanity with respect to Earth's life support system [44], there is a need to refocus LCE on the requirements needed to ensure absolute sustainability. The impact of a product must be viewed in the context of the full market volume and technical efficiency improvements will not suffice if consumption increases to support affluence and population growth [47]. When conventional efficiency improvements are not sufficient to meet the requirements for environmental sustainability in absolute terms with the current product technologies, then "the eco-efficiency limits are exhausted and a new eco-effective technology solution has to be sought, meaning that the path towards sustainability may require more fundamental function and system innovation" [48].

5. Conclusion

In this study, we predicted steel production's impact on climate change from 2015 to 2100 taking into account increasing population and affluence while keeping technology constant. We applied an in-use stock model and coupled this with a dynamic LCA model to estimate GHG emissions from steel production. The estimated GHG emissions were found to corroborate findings from previous studies. We found that under current technology, steel production would occupy around 50% of the safe operating space. This is clearly too large of a share for a single industry which leaves little room for other products and services. In conclusion, there is an urgent need for improving the environmental performance of steel production. Improvements on production technology and material efficiency are required from the production side while a reduction in material consumption is needed on the demand side. This presents a great future challenge which is of great importance if the humanity wants to protect the Earth System and live within the safe operating space.

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